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Research Report

High-Aspect-Ratio, Ultrathick, Negative-Tone Near-UV Photoresist and its Applications for MEMS

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Abstract

Detailed investigations of the limits of a new negative-tone near-UV resist (IBM SU–8) have been performed. SU–8 is an epoxy-based resist designed specifically for ultrathick, high-aspect-ratio MEMS-type applications. We have demonstrated that with single-layer coatings, thicknesses of more than 500 μm can be achieved reproducibly. Thicker resist layers can be made by applying multiple coatings, and we have achieved exposures in 1200-μm-thick, double-coated SU–8 resist layers. We have found that the aspect ratio for near-UV (400 nm) exposed and developed structures can be greater than 18 and remains constant in the thickness range between 80 and 1200 μm. Vertical sidewall profiles result in good dimensional control over the entire resist thickness. To our knowledge, this is the highest aspect ratio reported for near-UV exposures and resist thicknesses. These results will open up new possibilities for low-cost LIGA-type processes for MEMS applications. The application potential of SU–8 is demonstrated by several examples of devices and structures fabricated by electroplating and photoplastic techniques. The latter is especially interesting as SU–8 has attractive mechanical properties.

I. INTRODUCTION

The presence of high aspect ratios in very thick resists is not only interesting, it is often a requirement for fabricating micromechanical structures for MEMS or packaging applications. It allows vertical sidewalls of tall structures to be achieved with good dimensional control over the entire height. A well-known example is the **Li**thography, **G**alvanoforming, and **A**bformung process called LIGA [1], which makes use of X-ray lithography to pattern very thick PMMA (polymethylmethacrylate) layers used as templates for electroforming devices or shims for subsequent replication steps. X-ray lithography is an ideal technique to achieve high-aspect-ratio structures with submicron resolution in very thick resists because it features reduced diffraction, low resist absorption, and minimal proximity effects due to the absence of scattering. It has been demonstrated in many publications and by several groups that high-quality, X-ray exposed PMMA structures can be used as templates and shims for large-scale reproduction with submicron resolution in very thick layers with very good dimensional control over the entire structure height [2]. However, the cost of X-ray LIGA-type fabrication is greatly influenced by the expensive X-ray source (synchrotron radiation) and the demanding mask technology. Of course, the cost factor is less severe if very large volumes are mass produced using low-cost replication techniques. A substantial fraction of MEMS applications do not require submicron resolution, hence it would be very attractive if near-UV resists were available that have lower resolution (microns to tens of microns) and lower aspect ratios but otherwise with characteristics similar to PMMA/X-ray. Such an optical-lithography-based LIGA process technique would have great potential for low-cost MEMS fabrication. IBM [3,4] has recently announced a new resist (SU–8) that has the potential to fulfill the above profile. We have explored the limits of SU–8 in terms of its aspect ratio, resist thickness, and applicability to MEMS [5].

II. SU–8 RESIST PROPERTIES AND PROCESS

SU–8 is a negative, epoxy-type, near-UV photoresist based on EPON SU–8 resin (from Shell Chemical). The resist has been specifically developed for applications requiring high aspect ratios in very thick layers [6]. The key property that makes the SU–8 so attractive for ultrathick resist applications is its very low optical absorption in the near-UV range. This leads to a relatively good exposure dose uniformly over the entire resist thickness, which gives rise to vertical sidewall profiles and hence good dimensional control over the entire structure height.

The photoresist is prepared from commercially available components by dissolving an EPON resin SU–8 in an organic solvent GBL (gamma–butyrolacton). The quantity of the solvent determines the viscosity and hence the range of the possible resist thicknesses. Last, the photoinitiator, a triaryl sulfonium salt (10% of the EPON SU–8 weight), is mixed with the resin. Figure 1 shows the dependence of the resist thickness on the spinning speed. The resist is spun at low speed for a very short time using a conventional spin coater. Resist thicknesses up to 700 μm have been achieved with very good reproducibility by a single spinning of a viscous SU–8 dilution (70% of EPON SU–8) at a speed of 500 rpm for 10 s. Much greater thicknesses can be achieved by multiple coatings; we have demonstrated SU–8 thicknesses of 1200 μm made by double coatings. An additional advantage of SU–8 is its capability to self-planarize during prebake and hence to eliminate the edge-bead effect, which results in good contact between mask and resist in contact lithography.

Substrate/wafer stress due to thick resist coatings is a key issue for many applications. After prebake, a small tensile stress is introduced by the difference between the thermal expansion coefficients (TEC) of the wafer and SU–8. The stress is small because during the cooling phase of the prebake, polymer chain rearrangements take place in the resists that are not crosslinked. The resulting slight bowing of the wafer is very advantageous for contact-printing lithography because good mask/wafer contact is ensured. As we are working with resist thicknesses comparable to the wafer thickness, this stress can be high and consequently the wafer is bowed. Table I lists the measured bowing of a Si wafer coated with three different SU–8 thicknesses after pre-, post-, and hardbaking.

The main stress is generated as the crosslinked SU–8 cools down. The greater bowing measured after hardbake (Table I, see also Ref. [7]) is due to the higher baking temperature (200 °C). However, it is important to note that for most applications, hardbaking is not required; hence the subsequent discussion will deal only with postbaking. In addition to the thermomechanical stress introduced by the difference of the TECs, stress due to resist polymerization is also present. Figure 2 shows the evolution of wafer bowing during polymerization and cooling of a 3-inch, 300-μm-thick Si wafer coated with a 80-μm-thick SU–8 layer. It clearly demonstrates that bowing (stress) is introduced mainly during the cooling phase (for details, see Ref. [8]). The influence of the illuminated (polymerized) area on wafer bowing is shown in Table II. It shows that wafer bowing is strongly influenced by the illuminated (crosslinked) area. The illuminated area has been defined by exposed and developed areas of 1×1 cm, which are uniformly distributed over the wafer surface to achieve the 30 and 60% illuminated and polymerized area. The data in Table II are for a 3-inch, 380-μm-thick Si wafer coated with a 200-μm-thick SU–8 layer. Stress/bowing analysis for arbitrary shapes and areal coverage are currently being investigated, but in summary, the bowing (stress) of an SU–8-coated wafer can be lowered (i) by reducing the postbake temperature at the expense of baking time, (ii) by an appropriate mask design to reduce the illuminated area, and (iii) by choosing substrates that are a better thermal match for SU–8.

The spin coating, exposure, and development process for a single-layer resist of 500 μm thickness is as follows:

1. low-speed, short-time spinning (500 rpm for 17 s) with conventional spinner,
2. 3 h resist baking at 95 °C on leveled hot plate,
3. near-UV (400 nm) exposure with contact mask aligner (800 mJ/cm^2),
4. 95 °C postbake on level hot plate for 30 min,
5. development in PGMEA (propylene–glycol–methyl–ether–acetate) for 30 min,
6. if necessary, hardbaking at 200 °C for 30 min.

For multilayer coatings, steps 1 and 2 are repeated for each layer before exposure and development. The required exposure dose as a function of the SU–8 thickness is shown in Fig. 3. Stripping can be done either in hot NMP, some acid solutions, such as H_2SO_4/H_2O_2 or fuming HNO_3, and/or by O_2 ashing.

III. EXPOSURE RESULTS

All our exposure tests have been performed on SUSS M4A and MJB21 mask aligners in contact mode at 400-nm exposure wavelength. Figures 4, 5, and 6 demonstrate the SU–8 capabilities for resist thicknesses of 270, 500, and 1200 μm, respectively.

A small degree of nonverticality is noticeable. For instance, the structures shown in Fig. 6 have a top and bottom width of 65 and 45 μm, respectively, in a 1200-μm-thick resist from a mask width of 60 μm. This difference is due to the energy loss by absorption and spreading in the SU–8 layer. This can be minimized by increasing the dose and decreasing the mask width to compensate for overexposure effects. Nevertheless the ability to structure such fine lines in such a thick layer demonstrates the very low absorption of SU–8. Figure 7 shows a scanning electron microscopy (SEM) cross section through holes of different widths in a 730-μm-thick SU–8 structure. The smallest, fully developed structure has a width of 43 μm, resulting in an aspect ratio of 17. Our investigations of resist thicknesses between 80 and 1200 μm revealed that aspect ratios up to 18 can be achieved reproducibly. Sometimes a slight bending at the bottom of small trenches (as in Fig. 7) or pillows have been noticed. Such bendings can be eliminated by increasing the exposure dose and by postbaking first at 50 °C before the final postbaking at 95 °C.

All results reported here are based on standard dipping techniques for developing the exposed SU–8. We found a limitation to developing narrow openings (smaller than 4 μm), which is due to the difficulty of refreshing the developer in these small and deep holes. For that purpose other techniques such as spray developing or megasonic bath agitation may be necessary. The exposed material is highly crosslinked, resulting in a very low dilution rate in the developer. This is crucial because the developing step takes about 1 h for a 1200-μm-thick resist. It is also important to note that the developed structures are free of residues.

These results demonstrate the best capabilities known for near-UV exposed resists in terms of thickness and aspect ratio.

IV. MEMS APPLICATIONS OF SU–8

Given the capabilities of SU–8, the application scenery is very similar to X-ray-based LIGA but of course with reduced resolution and aspect ratio. On the other hand, all applications not requiring ultrahigh resolution can well be done at very low cost. Currently, we believe that the interest in MEMS-type applications within the capabilities of SU–8 is high.

In the following, we will present a few application examples of SU–8 for MEMS fabrication in the areas of electroplating, injection molding, and photoplastic devices [9].

A. Electroplating

The SU–8 fulfills the requirements placed on a mold for electroplating various devices such as gears and coils [4,5]. Figure 8 shows an example of an electroplated Cu coil, which can generate very localized and high magnetic fields. This example by no means reflects the limits of SU–8 in terms of thickness and aspect ratio but demonstrates its capabilities as an electroplating mold.

The potential of fabricating metallic mechanical structures with SU–8 electroplating masks is demonstrated by the flexible gear shown in Fig. 9 [10]. The flexible gear shape has been exposed and developed in a 200-μm-thick SU–8 layer, which was spin-coated onto a Si wafer with an Al sacrificial (200-nm) and a Au (30-nm) seed layer on top. Afterwards, the flexible gear was electroplated in a Ni bath and lifted off by diluted KOH, the Au seed layer being removed simultaneously. The springs connecting the outer ring with the inner axle ring are 50 μm wide.

B. Photoplastic and Plastic Injection Molding

In addition, we have explored EPON SU–8 material not only for masking and pattern transfer applications but also as a photoplastic material to fabricate micromechanical components. Photoplastic material means that the components are made of EPON SU–8 in only one or two process steps [9]. Preliminary investigations have shown that EPON SU–8 has interesting mechanical properties that make it attractive for applications as a photoplastic material.

Figure 10 demonstrates the capabilities of SU–8 as a photoplastic material to fabricate gears. Sacrificial layer techniques have been used to release the photoplastic components from the wafer after exposure and development. For this purpose the wafer was coated with a 200-nm-thick layer of Al prior to spin coating the SU–8. After exposure and development, the Al sacrificial layer is removed in an Al etchant (KOH 40% wt.) in order to release the structures. Sacrificial-layer etching takes place at a high rate, allowing large structures to be lifted off within a short time and without corroding the EPON SU–8. The gear shown in Fig. 10 has a diameter of 530 μm and a thickness of 200 μm.

As SU–8 is a negative-tone resist, it opens up interesting possibilities for the fabrication of three-dimensional structures by multiple spin coatings and exposures [11]. This feature is more difficult to achieve with positive-type X-ray LIGA. Figure 11 shows an example of a two-level SU–8 structure. The first level defines a big wheel, whereas the well-aligned second level forms the pinion.

These photoplastic structures are also the basis for fabricating metallic molds for plastic injection molding. We made metallic molds by starting with a photoplastic multilayer structure as shown in Fig. 12. While the structure is still on the wafer, it is completely covered with an evaporated thin metal layer (Cr/Au). The subsequent Ni electroplating forms the negative metallic structure of the photoplastic. The final injection mold is made by double-sided mechanical polishing and photoplastic stripping. Figure 13 shows the magnified section of the pinion structure in the Ni mold. The pinion diameter is 853 μm, and the Ni mold is 450 μm thick. This Ni mold is now used to fabricate low-cost plastic watch microparts by injection molding. This mold fabrication technique is an interesting alternative to today's wire electric discharge techniques to fabricate micromolds.

C. Other Applications

The high thermal stability ($T_g > 200\,^\circ$C for the crosslinked material) of SU–8 allows it to be used as a stable mask for deep silicon reactive ion etching (DRIE) [4]. Another interesting application of SU–8 multiple structures, the fabrication of embedded microchannels for microfluidic devices, is described in Refs. [11,12].

V. SUMMARY

We have explored the limits and applications of the EPON SU–8 near-UV photoresist for high-aspect-ratio, MEMS-type component fabrication. To our knowledge, this is the first demonstration of near-UV exposed and developed photoresist structures up to 1200 μm thick and having an aspect ratio of greater than 18. We believe that we have not yet reached the limit of thickness, whereas the aspect ratio seems to remain constant for the thickness range we have investigated (80–1200 μm). This has been found for dipping development; other development techniques such as spraying may increase the aspect ratio. The outstanding performance concerning SU–8's aspect ratio and thickness is predominately determined by the very low optical absorption in the near-UV range. As a result of this, the structures also show very vertical sidewall profiles, which are essential for good dimensional control in all three dimensions. Pattern transfer investigations by electroplating and injection molding confirmed the potential of SU–8 for LIGA-type device fabrication. We consider SU–8 a very attractive material for fabricating photoplastic micromechanical components because of its interesting mechanical properties and its low fabrication process costs. In conclusion, SU–8 has demonstrated outstanding performance for applications as a masking layer for pattern transfer by etching and plating, as well as being a new material for photoplastic device fabrication. Moreover, the use of standard UV photolithography provides the basis for very low-cost mass production of MEMS-type components and systems.

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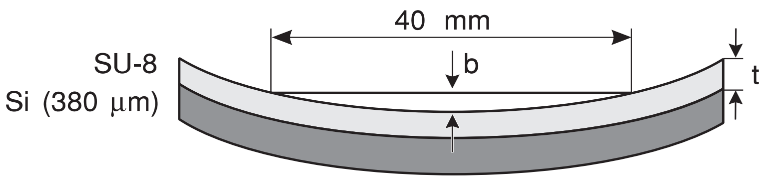
TABLE I. Wafer bowing due to the stress induced by the SU–8 layer. The bowing was measured over a 40-mm distance of a fully exposed 3-inch, 380-μm-thick silicon wafer. From [7], © 1997 IEEE.



SU–8 thickness	Additional bowing over 40 mm, b [μm]		
t [μm]	after prebake	after postbake	after hardbake
6.75	0	2	6
19	2	18	33
200	11	150	out of range

TABLE II. Wafer bowing due to the stress induced by a 200-μm-thick SU–8 layer. The bowing was measured over a 40-mm distance on three 3-inch, 380-μm-thick silicon wafers.

	Additional bowing over 40 mm, b [μm]	
% of illuminated area	after prebake	after postbake
30	4.45	82.1
60	5.2	115.5
100	11	141.1

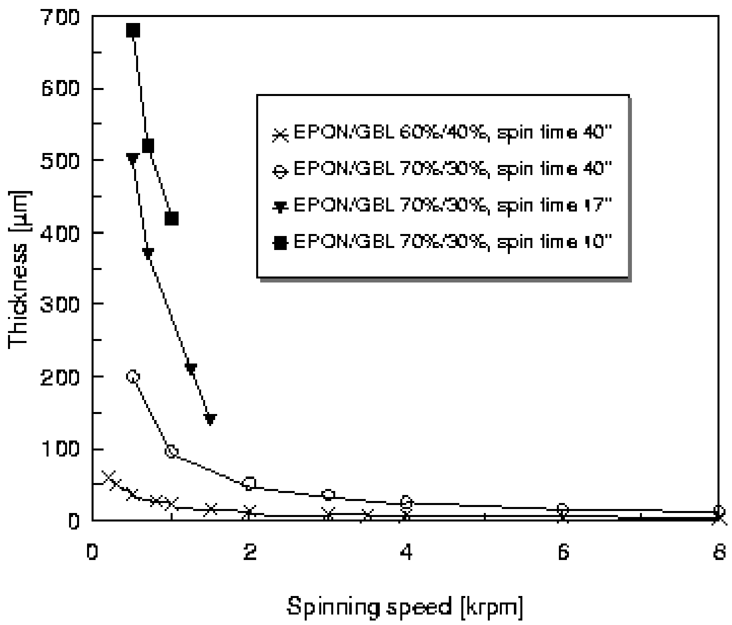


FIG. 1. SU–8 achievable thicknesses versus spinning speed, dilution rate, and spinning time. EPON/GBL dilution of 70%/30% covers thicknesses from 12 to 680 μm by single-spin coating on a 3-inch silicon wafer. From [7], © 1997 IEEE.

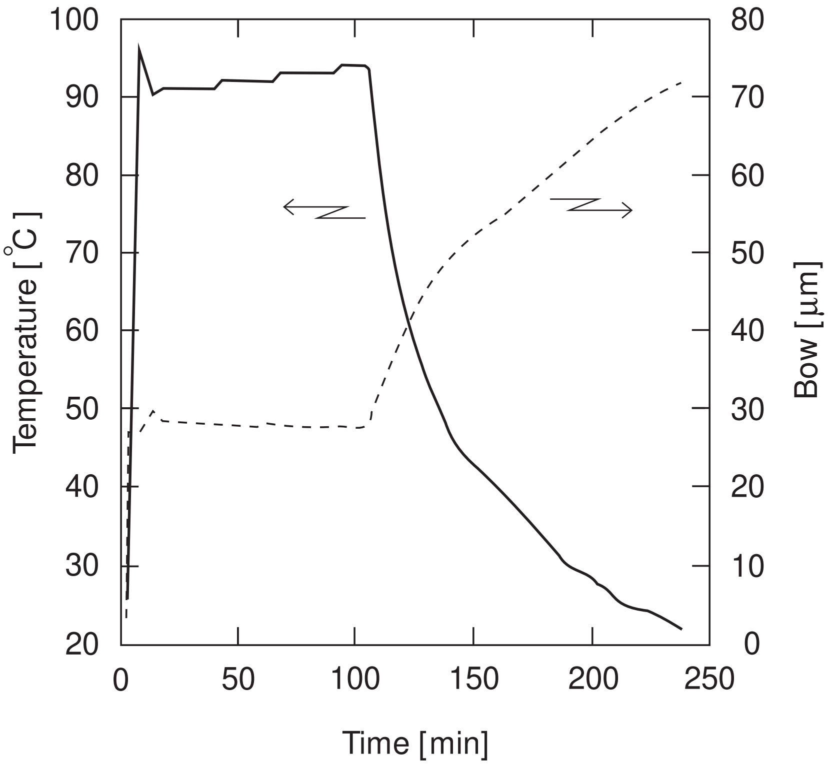


FIG. 2. Wafer bowing due to SU–8 stress as a function of postbake temperature and time. Wafer thickness: 300 μm; SU–8 thickness: 80 μm. Solid line: temperature; dashed line: wafer bow.

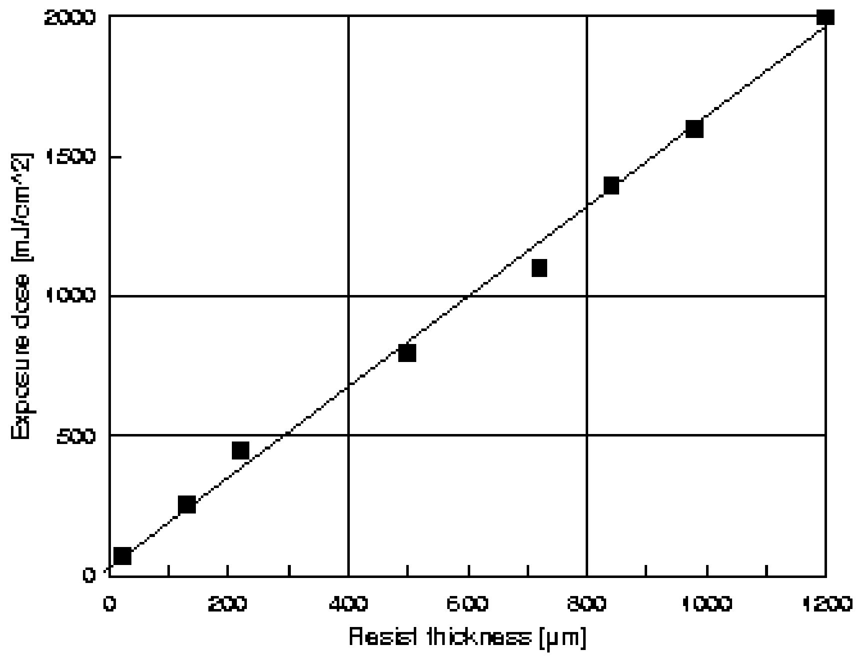


FIG. 3. Exposure dose versus the SU–8 thickness. From [7], © 1997 IEEE.

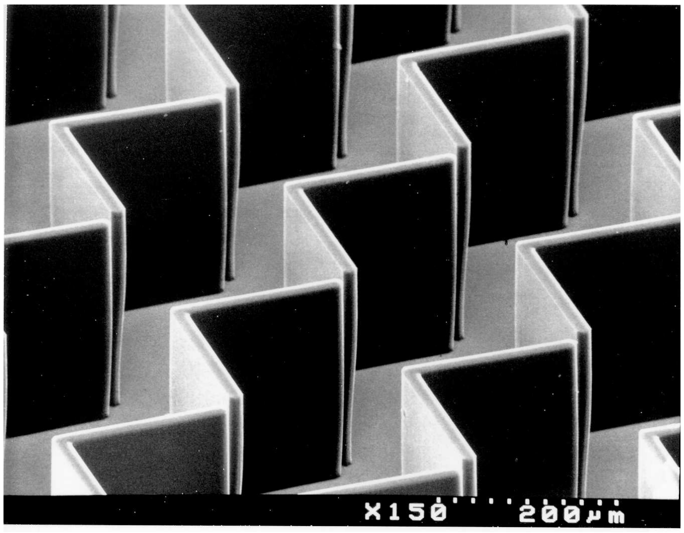


FIG. 4. SEM image of 270-μm-thick structures in SU–8 with a width of 16 μm, resulting in an aspect ratio of 17 (single-spin coated). From [7], © 1997 IEEE.

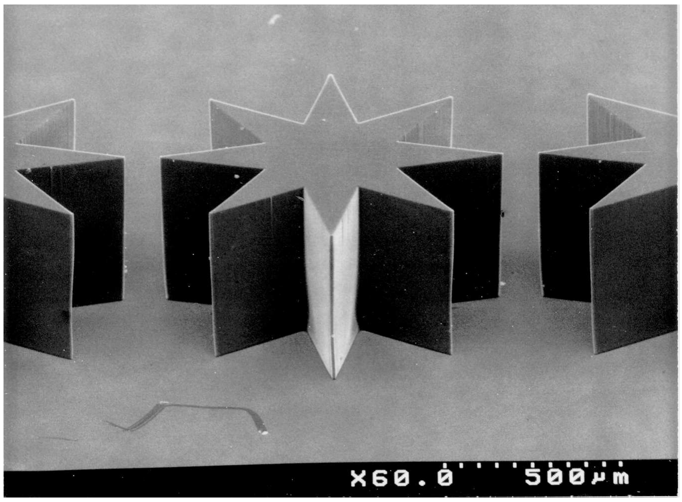


FIG. 5. SEM image of 500-μm-thick structures in SU–8 (single-spin coated). From [7], © 1997 IEEE.

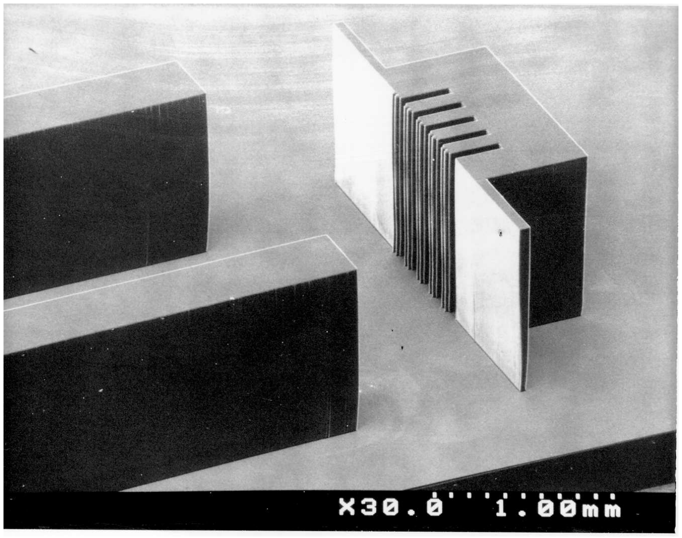


FIG. 6. SEM image of 1200-μm-thick structures in SU–8 with a line width of 65 μm, resulting in an aspect ratio of 18 (double-spin coated). From [7], © 1997 IEEE.

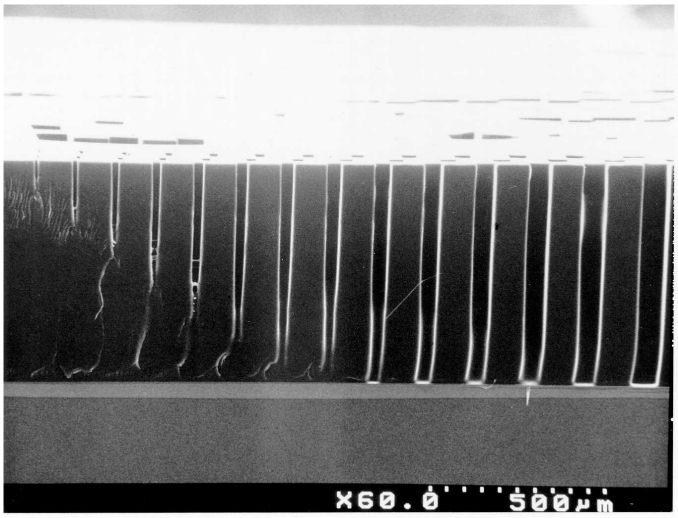


FIG. 7. SEM image of 730-μm-thick structures in SU–8 showing the actual trench width limit. The smallest completely developed structure has a width of 43 μm, resulting in an aspect ratio of 17 (double-spin coated). From [7], © 1997 IEEE.

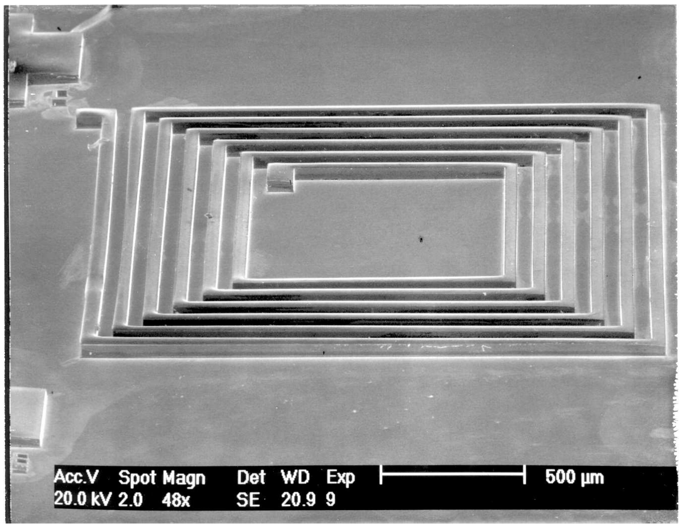


FIG. 8. SEM image of copper coil electroplated using an SU–8 mask. The coil pitch is 50 μm, the copper wires are 40 μm high and 25 μm wide. From [7], © 1997 IEEE.

FIG. 9. Electroplated, flexible Ni gear (diameter = 5 mm, thickness = 200 μm).

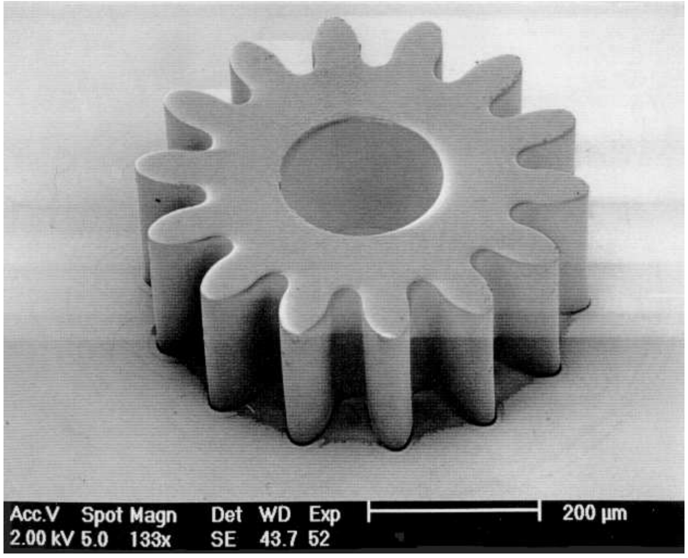


FIG. 10. SEM image of a photoplastic SU–8 gear that has been lifted off (diameter = 530 μm, thickness 200 = μm).

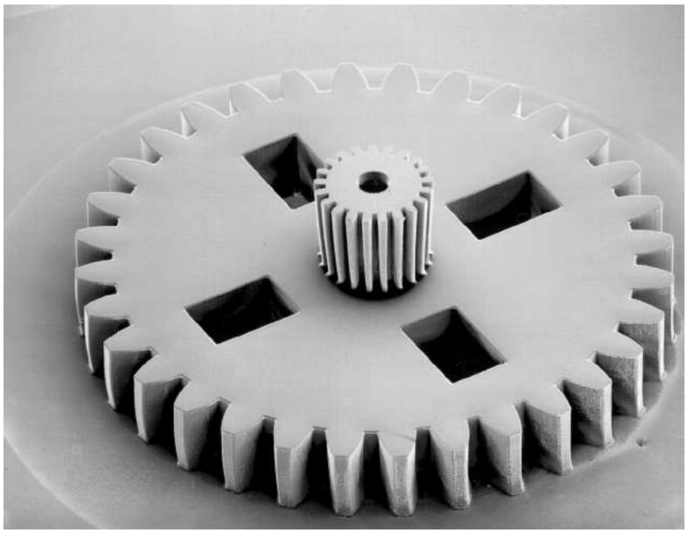


FIG. 11. Two-level, photoplastic gear.

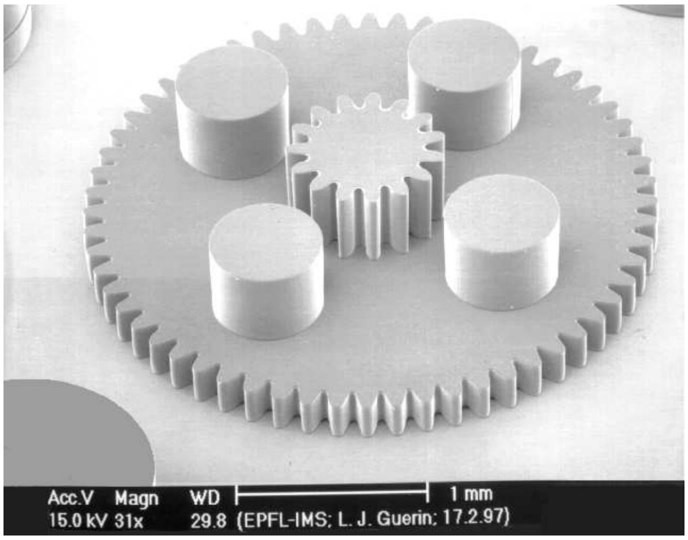


FIG. 12. Two-level, photoplastic SU–8 structure as basis for micromold fabrication.

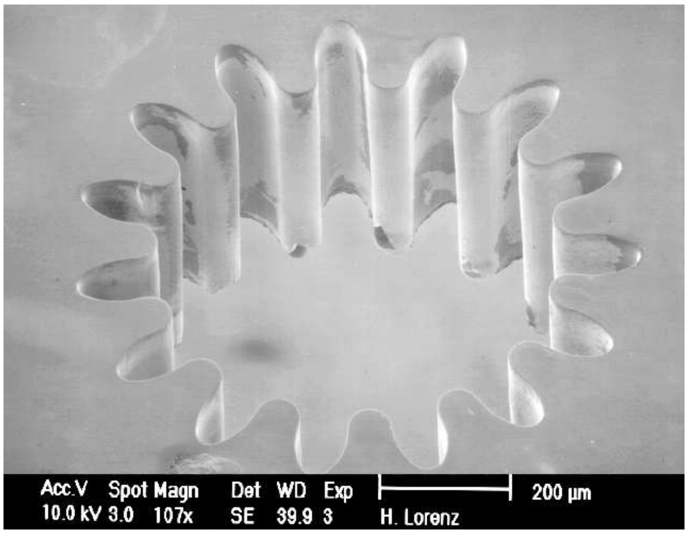


FIG. 13. Magnified view of the pinion area of the Ni micromold. (diameter = 853 μm, thickness = 450 μm).